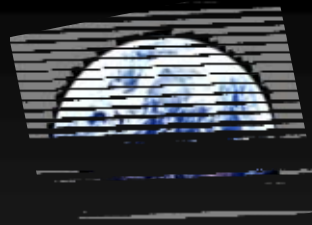


Title: In-Situ Resource Utilization (ISRU) to Support the Lunar Outpost and the Rationale for Precursor Missions

Session: B06, ISRU Links to Surface Systems

Abstract: One of the ways that the Constellation Program can differ from Apollo is to employ a live-off-the-land or In-Situ Resource Utilization (ISRU) supported architecture. The options considered over the past decades for using indigenous materials have varied considerably in terms of what resources to attempt to acquire, how much to acquire, and what the motivations are to acquiring these resources. The latest NASA concepts for supporting the lunar outpost have considered many of these plans and compared these options to customers' requirements and desires. Depending on the architecture employed, ISRU technologies can make a significant contribution towards a sustainable and affordable lunar outpost. While extensive ground testing will reduce some mission risk, one or more flight demonstrations prior to the first crew's arrival will build confidence and increase the chance that outpost architects will include ISRU as part of the early outpost architecture. This presentation includes some of the options for using ISRU that are under consideration for the lunar outpost, the precursor missions that would support these applications, and a notional timeline to allow the lessons learned from the precursor missions to support outpost hardware designs.



# In-Situ Resource Utilization (ISRU) to Support the Lunar Outpost and the Rationale for Precursor Missions

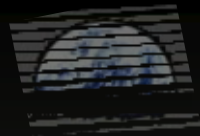
STAIF 2008

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# ISRU to Support the Lunar Outpost and the Rationale for Precursor Missions



## Contents:

- Living off the land, a sustainable architecture.
  - What is In-Situ Resource Utilization (ISRU)?
- The current customer requirements for ISRU at the lunar outpost.
  - What can ISRU provide?
- Earth based testing vs. lunar based testing.
  - What risks can be addressed via Earth based testing?
  - What risks cannot be addressed via Earth based testing?
- Precursor missions vs. experimental work at the early outpost.
  - Why not just perform ISRU experiments at the early outpost?
- Precursor missions to support ISRU outpost system deployment.
  - What missions would support the customer driven needs and timeline?
- Lunar ISRU Development & Mission Strategy.
  - What is the development plan?
- The timeline to support the early outpost using precursor missions.
  - When do precursors need to take place to influence the early outpost?

# Living off the land, a sustainable architecture. What is In-Situ Resource Utilization (ISRU)?

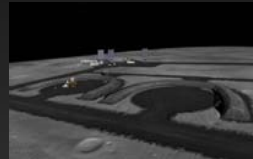
ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create products and services for robotic and human exploration

## In-Situ Lunar Resources

- 'Natural' Lunar Resources:
  - Regolith, minerals, metals, volatiles, and water/ice
- Discarded Materials
  - Scavenging of LSAM descent stage residual fuel, tanks, material, etc.
  - Crew trash and waste (after Life Support processing is complete)

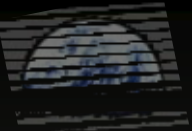
## Lunar ISRU Products and Services

- Site Preparation and Outpost Deployment/Emplacement
  - Site surveying and resource mapping
  - Crew radiation protection (In-situ water production or bulk regolith)
  - Landing area clearing, surface hardening, and berm building for Lunar Lander landing risk and plume mitigation
- Mission Consumable Production
  - Oxygen and/or water for life support, Extra Vehicular Activity (EVA), and propellant production
- Outpost Growth and Self-Sufficiency
  - Using in-situ materials in the production of structures, solar arrays, feedstock for fabrication and repair, and more...



# Living off the land, a sustainable architecture.

## What is ISRU? Cont'd

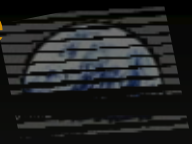


### Decisions from Lunar Architecture Development

- ISRU is a critical capability and key implementation of the VSE and sustained human exploration
- At the same time, ISRU on the moon is an unproven capability for human lunar exploration and can not be put in the critical path of architecture until proven
- Therefore, ISRU (as an end in and of itself) is manifested to take incremental steps toward the desired end state
- Architecture is designed to be open enough to take advantage of ISRU from whatever source when available



# The current customer requirements for ISRU at the lunar outpost. What can ISRU provide?



## Excavation of Regolith

### ▪ For Oxygen Production

- Excavation to make oxygen for life support and EVA usage requires either a small rover or part-time usage of a crew rover

### ▪ Landing pads and berms

- Largest outpost emplacement excavation requirement over life of outpost
- If landers are not moved, a new pad needs to be prepared *every 6 months*
- **Capability manifested on 1<sup>st</sup> landed mission in LAT Phase II**

### ▪ Habitat Protection

- Multiple options if regolith shielding for radiation or thermal is desired
- Trenching and inflatable covers evaluated for excavation impact

### ▪ Outpost Emplacement

- Excavate ramp or hole for nuclear reactor emplacement/shielding
- Prepare pathways for transferring cargo from lander
- Prepare trenches for cables

### ▪ For Science

- Prepare trenches for subsurface geologic/stratigraphy access for science
- Core extraction drilling for subsurface sample acquisition (resource characterization)
- Site preparation for antenna deployment

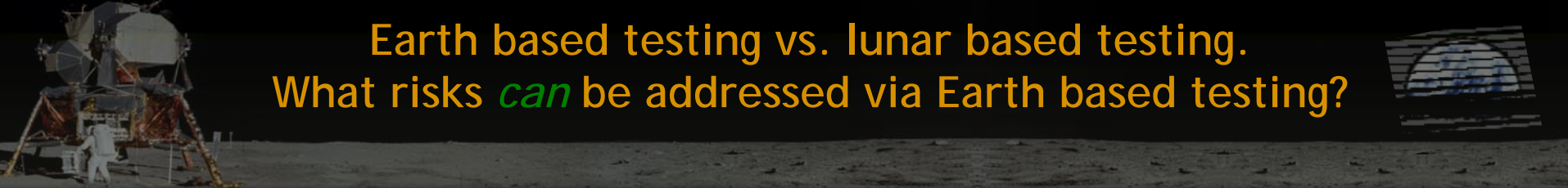
# The current customer requirements for ISRU at the lunar outpost. What can ISRU provide? Cont'd

## ISRU Consumable Production for Lunar Architecture

- O<sub>2</sub> Production from Regolith
  - 2 MT/yr production rate for EVA and life support makeup consumables
  - Capability manifested on 6<sup>th</sup> mission in LAT Phase II (before start of sustained crew)
  - Increased production to 10 MT/yr during outpost operation could also support refueling 2 ascent vehicles per year to further increase payload delivery capability
- In-Situ Water Production
  - Scavenge minimum of 55 kg of hydrogen (max. ~252 kg) from each lander descent stage after landing and add to in-situ oxygen to make 1 MT/yr of water
  - Polar water extraction not evaluated in Lunar Architecture Phase II effort. Not needed unless large scale in-situ propellant (O<sub>2</sub> & H<sub>2</sub>) production is required
- In-Situ Methane Production
  - Pyrolysis processing of plastic trash and crew waste with in-situ oxygen can make methane
  - Capability supports LSAM Ascent 'top-off' in case of leakage, power loss, or increased payload to orbit

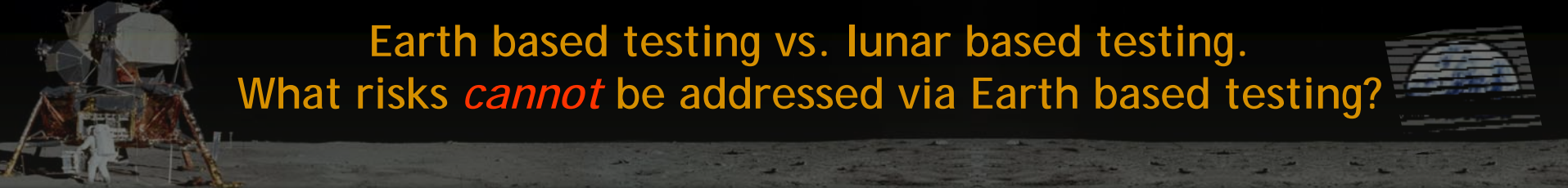
ISRU Processing Requirements	kg/yr (min.)
Oxygen Production	
For ECLSS & EVA	1000
For Water Production	800
For LSAM Ascent Propulsion	7600
Water Production	
For ECLSS & EVA (from in-situ O <sub>2</sub> + Scavenged H <sub>2</sub> )	900
Required H <sub>2</sub> Scavenged from LSAM Descent Stage	100
For radiation shielding (*one time production need)	1000 to 2000*
Water Electrolysis	
For ISRU	1125
For Night time Power	7335
For Pressurized Rover Power (45 kg/mission)**	1260
Methane Production	
For LSAM Ascent Propulsion (max)	2160

\*\* 28 excursions per year with at least 1 MPU



## Earth based testing vs. lunar based testing. What risks *can* be addressed via Earth based testing?

- Using *high-fidelity* lunar regolith simulants based on Apollo data:
  - Mass, volume, and power associated with ISRU hardware meets program allowance
  - Excavation efficiency
  - Process extraction efficiency
- Using ambient laboratories
  - Long duration life testing
- Using lunar analog field sites
  - Integrated operation and interfaces of all ISRU and Surface System elements, especially with International Partners
- Using *high-fidelity* lunar environment simulation
  - Environmental compatibility of ISRU hardware

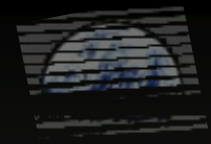


## Earth based testing vs. lunar based testing.

### What risks *cannot* be addressed via Earth based testing?

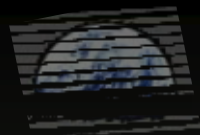
- Uncertainty in *actual* vs Earth demonstrated capabilities in excavation and material transport due to:
  - Uncertainty in material compaction and physical properties for areas outside of Apollo experience
  - Increased wear and decreased life due to lunar simulant inability to represent correct size, shape, and abrasive properties
  - Inability to excavate or move material due to material bridging or inadequate force/torque
- Uncertainty in actual vs Earth demonstrated processing rates and extraction efficiencies due to:
  - Uncertainty of local resource distribution leading to lower concentrations of expected feedstock
  - Impact of variability of feedstock materials on processing
  - Impact of unknown contaminants
  - Increased wear and decreased life due to lunar simulant inability to represent correct size, shape, and abrasive properties
- Uncertainty in long-duration life and maintenance due to cost of analog and environment simulation for extended periods of time

# Precursor missions vs. Experimental work at the early outpost



- Why not just perform ISRU experiments at the early outpost?
  - Benefits of ISRU for mass, cost, or risk reduction are not incorporated into the architecture from start
    - Lower long-term payback
  - Surface systems ISRU provides services to, such as propulsion, power, life support, and/or EVA may require major change
    - $\text{LO}_2/\text{CH}_4$  vs storable propellants for lunar ascent
    - Liquid oxygen vs gaseous oxygen for EVA and power
- Chicken and the Egg?
  - One point of view, **does the chicken or the egg come first?**
    - Egg first: Prove ISRU technologies on precursor missions in time to influence the early outpost architecture and hardware designs
    - Chicken first: Set up the core of an outpost with ISRU-compatible Earth supplied consumables first and then add on ISRU to develop and reduce later costs
  - Second point of view, **will we develop a chicken at all?**
    - To get to a chicken we must start with an egg
    - Use precursor missions to learn what options exist to leverage natural resources to reduce outpost (early and long term) costs

# Precursor missions to support ISRU outpost system deployment



What missions would support the customer driven needs and timeline?

- a) Prospecting mission to investigate local resources
  - ❖ Develop technologies that buy down risk on outpost system for water collection and landscape management
- b) Notional Outpost Risk Reduction LPRP Mission
  - ❖ Develop lunar outpost surface system and ISRU technologies that buy down risk of outpost and oxygen production and landscape management
  - ❖ Partner with other technology areas that would benefit from a precursor mission

## a) Prospecting Mission to Investigate Local Resources



- Mission Concept & Purpose
  - How much hydrogen or water?
  - What else is there?
  - How spread and deep is it?
  - How difficult (hardware & energy) is it to get out?
  - Are the regolith properties different than Apollo?

# a) Prospecting Mission to Investigate Local Resources

## ***RESOLVE Project Objectives:***

- The objectives of the Regolith and Environment Science & Oxygen and Lunar Volatile Extraction (RESOLVE) project are to develop, integrate, and demonstrate technologies and processes that can be used to:
  - Demonstrate oxygen extraction from lunar regolith & process performance characterization
  - Determine the form & amount of hydrogen/water & other volatiles on the moon
  - Determine regolith physical & mineral properties for excavation & processing
  - Demonstrate technologies that can be scaled up for outpost use

## ***Recent Milestones:***

- 1st generation Engineering Breadboard Unit (EBU1) Development & Testing Complete
  - Sample extraction, transfer, metering, & crushing (Fig. 1)
  - Sample heating, hydrogen/water volatile content & quantity measurement, hydrogen/water capture, & water electrolysis (Fig. 2)
  - Oxygen extraction from regolith demonstration system (Fig. 3)
- Mineral characterization instrumentation (Fig. 4) is still in assembly but optical layout successfully completed
- 1st generation sample extraction, transfer, metering, and crushing assembly was integrated with a surface mobility unit under development by GRC/Carnegie Mellon University for ETDP HRS Project (Fig. 5)

## ***Upcoming Plans:***

- Results and lessons learned from design, fabrication, and operation will be applied to 2nd generation EBU (EBU2) and field demonstration in 2008



Fig 1: NORCAT Drill, Sample Transfer, Metering Device, & Crusher Assembly



Fig 2: Volatile oven, gas chromatograph, hydrogen/water capture, & water electrolysis



Figure 3: Oxygen extraction from regolith demonstration system

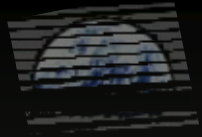


Fig 4: Raman-CHAMP Instrument (RCI)



Fig 5: RESOLVE drill on Scarab Rover

## b) Notional Outpost Risk Reduction LPRP Mission



- Mission Concept & Purpose
  - Fly as much relevant outpost surface element (and LSAM) technology and hardware as possible 6 to 8 years before outpost deployment so that performance and lessons learned can be applied to the final outpost design.
  - Demonstrate oxygen production from regolith, and liquefaction and storage of oxygen on lunar surface early enough to still influence design for the life support logistics carrier, EVA portable life support backpack, and surface fuel cell and night time power storage and distribution design for outpost.

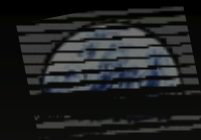
## b) Notional Outpost Risk Reduction LPRP Mission

- Outpost Precursor Testbed based on an ISRU and Modular Architecture (OPTIMA) Project Objectives
  - “Dust to thrust”
  - ISRU technology development to support producing 1 metric ton of oxygen per year
  - Set up a modular development program such that different technologies can be tested in the end to end system
  - Current partnerships with NASA for November 2008 testing include
    - Lockheed Martin, Orbital Technologies, Physical Sciences Inc.
    - Department of Energy (PNNL--Battelle)
    - ETDP Human Robotic Systems (HRS), Thermal, Cryo Fluid Management (CFM), and likely others over time

# Lunar ISRU Development & Mission Strategy

- ISRU will be demonstrated and incorporated into the lunar architecture in 3 Phases:
  - Phase 1 Proof-of-concept & Concept Validation (Earth based)
  - Phase 2 Risk Reduction for Outpost (Precursor missions if possible)
  - Phase 3 Outpost Deployment and Operation (Profit to the architecture)
- ISRU benefits of Phase 2 to support Phase 3:
  - Determine the amount of solar wind volatiles (esp. hydrogen) outside of the permanently shadowed crater to (a) compare to LRO & Apollo, and (b) understand resource potential in case hydrogen source in permanently shadowed crater is not available for use.
  - Perform excavation to regolith geotechnical characterization to provide engineering and operation data for subsequent designs
  - Perform regolith processing to extract oxygen to prove concept and critical operation and design parameters

# Lunar ISRU Development & Mission Strategy Cont'd

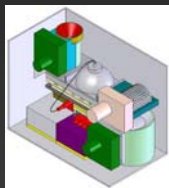


## LPRP/Sortie Demonstrations

Phase 1 (Prove Concept)

Phase 2 (Reduce Risk)

### Oxygen Production Polar Rim Regolith



Oxygen  
Production  
Proof-of-  
Concept



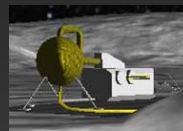
**Purpose:** Demonstrate feasibility of oxygen production technique

- Proof-of-concept; 1 operation min., multi-operation desired
- Evaluate ability to extraction of silicon and metals from regolith
- Perform regolith excavation and characterize performance to design rover excavator

### Excavation & Scaled O<sub>2</sub> Production Demo



Regolith Excavation  
& Transport



Regolith Processing  
for O<sub>2</sub> Demo

**Purpose:** Demonstrate subscale extraction & oxygen production

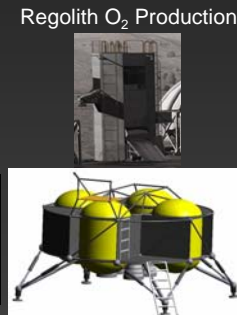
- Demonstrate excavation and oxygen production operation & life



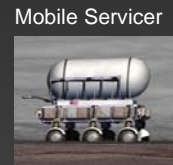
### Oxygen Production from Regolith



Regolith Excavation  
& Transport



Modified LSAM -  
Oxygen Storage



Mobile Servicer

Oxygen  
Transport

# Lunar ISRU Development & Mission Strategy Cont'd

## LPRP/Sortie Demonstrations

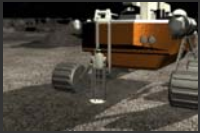
## Outpost Capability

Phase 1 (Prove Concept)

Phase 2 (Reduce Risk)

Phase 3 (Deploy for Use)

### Polar Crater Resource Characterization



### Polar Water Extraction Demo



### Water-O<sub>2</sub>/H<sub>2</sub> Production from Polar Crater

Regolith Excavation & water/hydrogen extraction in one unit



Water Transport (out of crater)

Water Processing



Modified LSAM – O<sub>2</sub> & H<sub>2</sub> Storage

Mobile Servicer



Oxygen Transport



Hydrogen Transport

Regolith Excavation & water/hydrogen extraction in one unit

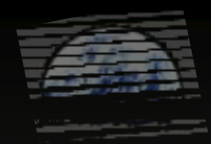
**Purpose:** Demonstrate subscale water extraction & transport

- Demonstrate excavation & separation system
- Demonstrate operation in permanently shadowed crater
- Demonstrate ability to take water out of crater

**Purpose:** 'Prospect' & characterize polar water/hydrogen

- Is it H<sub>2</sub> or H<sub>2</sub>O?
- What else is there?
- How spread and deep is it?
- How difficult is it to get out?
- Are the regolith properties different than Apollo?

# The timeline to support the early outpost using precursor missions



- When do precursors need to take place to influence the early outpost?

